A 10-GHz Amplifier Using an Epitaxial Lift-Off Pseudomorphic HEMT Device

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***Abstract*— A process to integrate epitaxial lift-off devices and microstrip circuits has been demonstrated using a pseudomorphic HEMT on an alumina substrate. The circuit was a 10 GHz amplifier with the interconnection between the device and the microstrip circuit being made with photolithographically patterned metal. The measured and modeled response correlated extremely well with a maximum gain of 6.8 dB and a return loss of -14 dB at 10.4 GHz.**

I. Introduction

In 1978, Konagai *et al.* [1] demonstrated that a thin film of GaAs based material could be removed from it's growth substrate using a preferential etch of a buried AlAs layer. It is well known [2] that AlAs etches in HF:DI (1:10) at a rate 10^7 times faster than $Al_xGa_{1-x}As$ when x is less than 0.4. Also, because of the unique relationship between the lattice constant of AlAs–GaAs based materials, a structure can be made on GaAs that has a thin layer of AlAs grown between the substrate and the active device layer. The active layer is then later easily removed from the substrate via a HF etch of the AlAs sacrificial layer and the thin active layer can be attached to a limitless number of host substrates.

Work on epitaxial lift-off (ELO) techniques has progressed from optoelectronical devices [3], [4], to active circuits [5], and to microwave applications [6]–[8]. Shah *et al.* [6] demonstrated a MESFET device that had been fabricated after ELO which resulted in a $f_{\max}$ of 14 GHz. Van Hoof [7] demonstrated a MESFET that had been fabricated before ELO. They compared device properties to see the effects of the ELO step and found some degradation in the extrinsic transconductance due to ELO. The focus of our research has been in the area of microwave applications with a distinct focus on active devices. Recently, we fabricated high-electron mobility transistors (HEMT) and estimate the effects of the ELO step on HEMT device characteristics [9], [10]. We found no degradation in the performance of the devices, but rather an enhancement of f_T and the low-frequency gain. It was shown by Mena *et al.* [11] that an enhancement in the 2-D carrier confinement was detected after ELO, which would, in turn, explains the improvement in the gain of the HEMT device.

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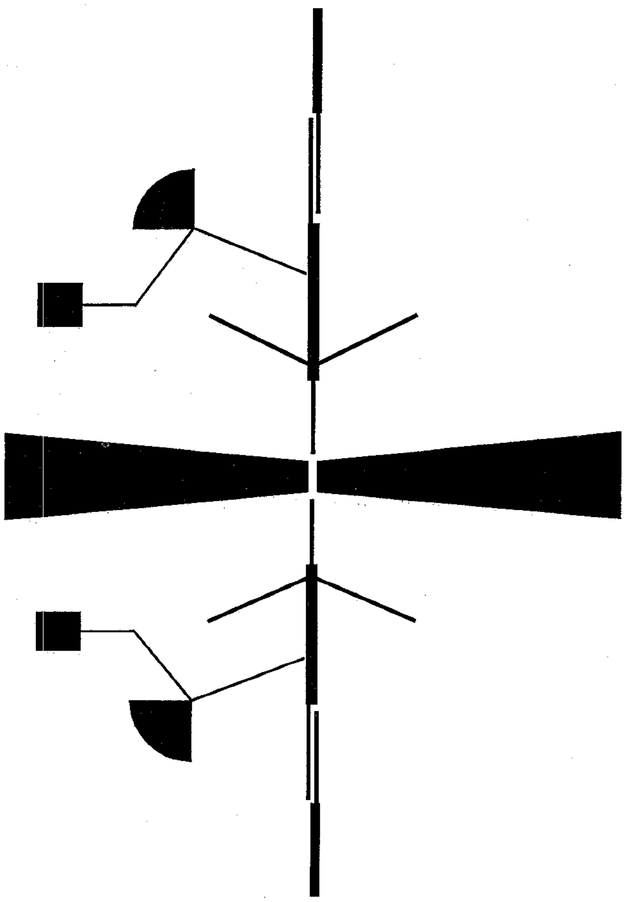
The purpose of making ELO devices is to independently optimize device and substrate properties in microwave circuit design. Here, for the first time, we present the integration of an ELO pseudomorphic HEMT (P-HEMT) device on a microwave substrate to fabricate a 10-GHz amplifier. The design will use a discrete ELO transistor attached to an alumina substrate. A classical, narrow band amplifier was designed using open circuit stub match and the typical scattering parameters of an ELO PHEMT device. Contact between the circuit and the PHEMT ELO device was made via photolithographically patterned metal lines. These interconnect lines step from the alumina substrate to the device, without the need of bondwires.

II. Fabrication

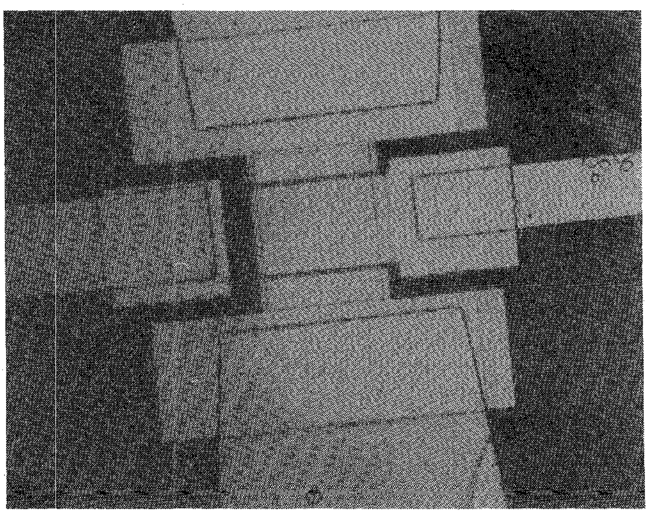
The P-HEMT structure was MBE grown material, provided by QED Corporation, consisting of a $Al_{0.23}Ga_{0.77}As$–$In_{0.2}Ga_{0.8}As$–GaAs quantum-well structure with silicon pulse doping in the wide-band $Al_{0.23}Ga_{0.77}As$ region. A 500-Å AlAs release layer was grown between the GaAs substrate and the superlattice to enable the ELO step. Varied thicknesses of the AlAs sacrificial layer from 50 to 1000 Å were evaluated and no significant difference in the ELO capability was detected.

Device fabrication started with a mesa isolation process that etched approximately 1500 Å of material to insure isolation while avoiding the AlAs layer. Ohmic contacts were formed using Au–Ge–Au–Ni–Au alloyed for 15 seconds at 400° C. Contact composition and alloying parameters are critical in maintaining good contact resistivities after ELO. Because of the extreme flexing of the thin film after ELO, the contacts must be able to withstand large angles of flexing without damage. Ti–Au gates were used to form 0.8-, 1.0-, and 1.2-μm gate lengths. The structure uses a dual 100-μm gate finger design to form a 200-μm gate width with a source to drain separation of 4 μm.

The ELO step was done using an apiezon wax coating of approximately 30-μm thick on the front side of the sample and cured at 150°C for 30 minutes. This gives the wax a compressive force to help facilitate the ELO step and protects the active device. The sample edges were cleaned and subjected to a preferential etch of hydrogen peroxide:ammonia hydroxide to remove the exposed active edge layer, leaving the AlAs release layer exposed [12]. The samples were then allowed to etch in a diluted HF solution overnight at room temperature to release the active layer from the GaAs substrate. Samples were attached to the alumina substrates and adhesion



(a)



(b)

Fig. 1. (a) Microstrip amplifier design on alumina. (b) Actual ELO device with microstrip contacts.

of the device was achieved via Van der Waals forces. To improve adhesion for further circuit processing and to allow for more stable device measurements, the devices were coated with a spin-on glass (SOG) and cured at 250°C for 4 hours. The SOG also improves the metal step coverage over the 8000-Å step generated by the ELO film and the alumina substrate [10]. A classical narrow-band, high-gain amplifier

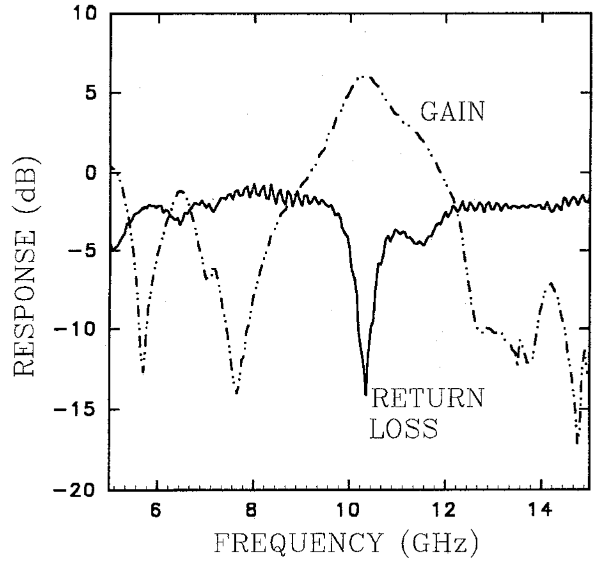


Fig. 2. Gain and return loss response of the amplifier circuit at −10-dBm input power.

was designed using EESOF™ with a center frequency of 10 GHz and optimized for a 10 mil alumina substrate. The microstrip circuit consist of one quarter wavelength coupled line dc blocks, series/shunt microstrip matching networks and bias networks that use a 1/4 wavelength high-impedance line cascaded with a 1/4 wavelength radial stub to provide RF isolation. The amplifier transmission lines were formed with a metal lift-off process after the ELO device was attached using 1.6 μm of gold. Contact between the transmission lines and the finished amplifier were made by opening contacts through the SOG. The amplifier design and finished active device are shown in Fig. 1(a) and (b), respectively.

III. Results and Discussion

The circuit was mounted into a custom designed package utilizing coaxial connectors. Measurement of the device was done on a HP8510B based automatic network analyzer and the bias of the circuit was adjusted for optimum output performance.

The gain and return loss are shown in Fig. 2 for the finished circuit. A small signal gain maximum of 6.8 dB was measured at 10.4 GHz at a gate bias of –1.8 volts and drain bias of 3 volts. This compares with the modeled gain maximum of 9.2 dB with a design bandwidth of 1 GHz. However, the modeled response did not take into account such parameters as connector loss, radiation losses or an imperfect ground plane. The grounding used for this design was a front side ground plane created via a tapered 1/2 wavelength line to physical ground. Experimentally it was shown that the ground plane was sensitive to the slight variations in shape and imperfections that tended to degrade the amplifier gain. The return loss for the amplifier is a much narrower bandwidth than the gain response with a minimum of –14 dB at 10.4

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GHz and a –2 dB out of band response. The data was taken at a −10 dBm input rf power level.

There was a strong correlation between the shape and frequency tracking of the modeled and measured data. In a circuit that utilizes standard discrete HEMT devices, it is difficult to predict the effect of bondwire length at the input, output and ground plane of the device. With ELO devices, the effect of bondwires are eliminated and the interconnecting lines between the circuit and the discrete device can be modeled accurately. The SOG was also investigated to determine its effect on RF device performance and it was determined to be negligible.

IV. Conclusion

An ELO P-HEMT discrete device was used in a narrow band amplifier design on an alumina substrate. The interconnection between the discrete device and the transmission lines of the alumina substrate were photolithographically defined eliminating the need for bondwires. The gain of the circuit was 6.8 dB and the return loss minimum was −14 dB at 10.4 GHz. This is the first reported use of a ELO P-HEMT device in a microwave circuit and demonstrates the feasibility of such a process for microwave applications.

Some of the advantages of using ELO devices and optimized substrates in microwave circuit design are: reduced substrate losses of the transmission lines; smaller transmission lines by using substrates with a smaller effective wavelength ($\lambda_{\rm eff}$), i.e., 20% reduction in $\lambda_{\rm eff}$ when the substrate ϵ_r is increased from 13.1 to 20 at 10 GHz; better substrate power dissipation; lower engineering cost associated with circuit tuning and redesigns; and the integration of devices with dissimilar profiles such as diodes, FET's, optoelectronic, and passive components.

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